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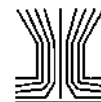
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# Development of a High Volume Slit Nozzle Virtual Impactor to Concentrate Coarse Particles

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This paper presents the development and evaluation of a high volume slit nozzle virtual impactor that can be used to concentrate coarse particles (2.5–10  $\mu\text{m}$ ) for inhalation studies. A variety of physical design and flow parameters were evaluated for their effects on the virtual impactor performance. To increase the impactor sampling flow, both multinozzle and longer slit configurations were developed and tested. The use of a longer slit nozzle made it possible to increase the inlet flow more effectively than using multiple nozzles. The effect of the slit nozzle length (from 0.762 cm up to 6.35 cm) on the impactor performance was examined. It was observed that increasing the slit length did not significantly diminish the performance of the impactor to concentrate coarse particles. Furthermore, a wider slit ( $W_1 = 0.363$  cm) that operates at a slightly higher pressure drop was used to increase the sampling flow rate. Although the wider slit presented greater losses for fine particles, the concentration factor for coarse particles was just as good as with the original narrower slit ( $W_1 = 0.305$  cm). Finally, it was demonstrated that a single-stage slit impactor ( $L = 6.35$  cm,  $W_1 = 0.363$  cm,  $Q_0 = 870$  L/min) can be used to increase the coarse particle concentration by a factor of 15 and to supply a flow of 43.5 L/min for animal or human exposure studies. A higher concentration factor, up to 50, was achieved by using a smaller minor-to-total flow ratio.

## INTRODUCTION

A number of mortality studies (Fairly 1990; Pope et al. 1991, 1992; Schwartz and Morris 1995) have shown significant associations between high levels of airborne particles and adverse respiratory and cardiovascular effects, including hospital admissions for bronchitis and asthma, longitudinal changes in peak flow rates, respiratory symptoms, and medication use. It is be-

lieved that the particles responsible for the observed adverse health effects are those with aerodynamic diameter  $<10 \mu\text{m}$ , because these “inhalable” particles are small enough to penetrate deeply into the respiratory system. However, numerous laboratory animal inhalation studies using artificial preparations have demonstrated moderate or no effects, even at concentrations much higher than those typically found in ambient air (Avol et al. 1988; Hackney et al. 1989; Anderson et al. 1992). The discordance between laboratory and epidemiological studies may be explained by the reliance of the laboratory studies on the controlled-chamber exposures to single chemical component particles or simple mixtures of a few components. Such artificial particles are not an adequate simulation of ambient inhalable particles, which typically consist of a mixture of a large number of compounds, such as sulfate, nitrate, ammonium ions, sea salt, organic and elemental carbon, a variety of trace elements, and even pollens. The components of ambient particles may interact with each other to create toxic effects not found with artificially generated atmospheres (Lippmann 1989). Thus there is a need to use ambient particles directly for inhalation studies. However, typical ambient particle concentrations, particularly for coarse particles, are usually too low to perform effective inhalation studies.

Virtual impactors can be employed to concentrate particles of a desired size range. Recently a three-stage virtual impactor system has been developed to increase ambient fine particle ( $0.15 \mu\text{m} < d_p < 2.5 \mu\text{m}$ ) concentrations by up to a factor of 30 (Sioutas et al. 1995). Particles above the impactor cut-off size are separated from gases and collected in the minor flow. Phase separation occurs in a few microseconds, thus the concentrated particles are in equilibrium with the existing ambient gaseous pollutants. Furthermore, the concentration of gaseous pollutants (such as  $\text{O}_3$ ,  $\text{SO}_2$ ,  $\text{HNO}_3$ ) can be controlled by either addition through injection or removal using diffusion denuders.

Due to the fact that the low cutpoint virtual impactor has poor particle separation characteristics and relatively large internal losses of small particles (Sioutas et al. 1994), the actual concentration factor is considerably lower than the nominal factor, which is equal to the ratio of the total flow to the minor flow. As a result, in order to obtain 50 L/min of fine particle

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flow concentrated by a factor of about 30 times, the total inlet flow of the three-stage virtual impactor system must be over 6000 L/min. The concentration process for coarse particles is expected to be easier because of better separation performance of the virtual impactors at a higher cutpoint (Wang and John 1988; Marple et al. 1991). However, the concentration factor for coarse particles should be higher than for fine particles because coarse particles are usually present in ambient air at a lower concentration than fine particles. As a result, a coarse particle concentrator should still operate at high flows.

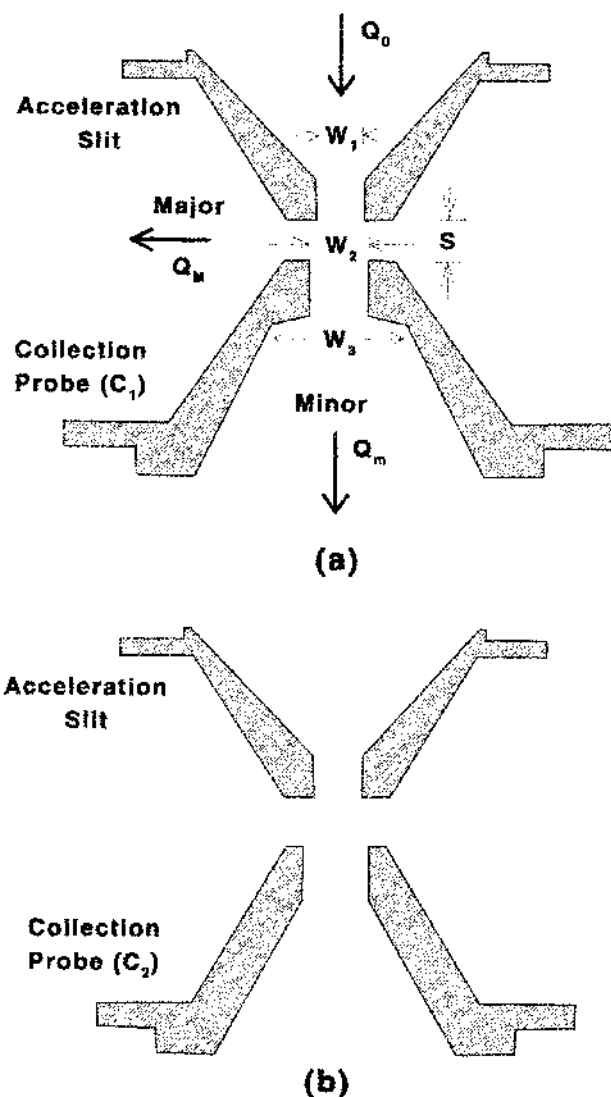
A high volume virtual impactor based on a single nozzle has the problem of high pressure drop across the impactor (Marple et al. 1990). This increased pressure drop may cause significant losses of semivolatile components from ambient particles, which may be of toxicological importance (Nishioka et al. 1988; Kelly et al. 1994). Multinozzle high volume impactors operate with a relatively lower pressure drop, but they require precise alignment between the acceleration and collection nozzles. Another problem with multinozzle high volume impactors is that they require a relatively large space between nozzles to minimize multiple jet interaction, which can affect the impactor performance (Fang et al. 1991). Recently, a  $2.5\ \mu\text{m}$  cutpoint slit nozzle virtual impactor was developed which operates at a low pressure drop (Ding and Koutrakis 1999).

In this paper we present the development of a virtual impactor that can be used to concentrate ambient coarse particles while keeping them suspended in air and without altering their size distribution and physicochemical characteristics. This new virtual impactor will make it possible to construct a particle concentrator, which can be used to investigate the health effects of ambient coarse particles under a real-time and dynamic condition.

## METHODS

The design of a slit nozzle virtual impactor is illustrated in Figure 1.  $Q_0$  is the total inlet flow,  $Q_m$  is the minor flow,  $Q_M$  is the major flow,  $W_1$  is the acceleration slit width,  $W_2$  is the collection slit width, and  $S$  is the gap between the acceleration and collection slits. The slit length ( $L$ ) is not shown in this figure. Coarse particles larger than the impactor cutpoint ( $2.5\ \mu\text{m}$ ) keep going straight and enter the collection probe ( $C_1$  or  $C_2$ ), while fine particles follow the deflected air streamlines to the major flow. As a result, the coarse particles are collected in the minor flow and are concentrated by a nominal factor of  $Q_0/Q_m$ , while the fine particle concentration in the minor flow remains at its original value.

Two prototypes (I & II) of slit nozzle virtual impactors were developed and tested. Their design and experimental parameters are shown in Table 1. Prototype I was designed to have an acceleration slit width of  $W_1 = 0.305\ \text{cm}$ , the same as the diameter of the acceleration round nozzle of the dichotomous sampler (Loo and Cork 1988), and a collection slit width of  $W_2 = 0.427\ \text{cm}$ . The slit length was relatively short,  $L = 0.762\ \text{cm}$ . The gap ( $S$ ) between the acceleration and collection slits was adjustable. In addition, two different collection probes ( $C_1$  and  $C_2$ ) were built



**Figure 1.** Cross section view of the slit virtual impactor: (a) a slit virtual impactor using collection probe  $C_1$ ; (b) a slit virtual impactor using collection probe  $C_2$ .

to investigate the effect of the cavity shape below the collection slit on the particle concentration factor. The collection probe ( $C_1$ ) shown in Figure 1a has an abruptly enlarged cavity directly below the slit,  $W_3 = 1.0\ \text{cm}$ , while  $C_2$  (Figure 1b) does not. Both collectors have a slit width of  $W_2 = 0.427\ \text{cm}$  and a slit length of  $0.762\ \text{cm}$ . Furthermore, multiple rectangular nozzles ( $n = 3$  and  $5$ ) were also developed based on Prototype I. All the nozzles were constructed in a line as shown in Figure 2a. The space between two adjacent nozzles was  $2.54\ \text{cm}$  so as to minimize multiple jet interactions.

Prototype II was developed to have a wider slit width ( $W_1 = 0.363\ \text{cm}$ ) in order to increase the flow rate per unit slit length. Only collection probe  $C_1$  was used in Prototype II. The collection slit width was increased to  $W_2 = 0.508\ \text{cm}$ , maintaining the

**Table 1**  
Summary of design and experimental parameters

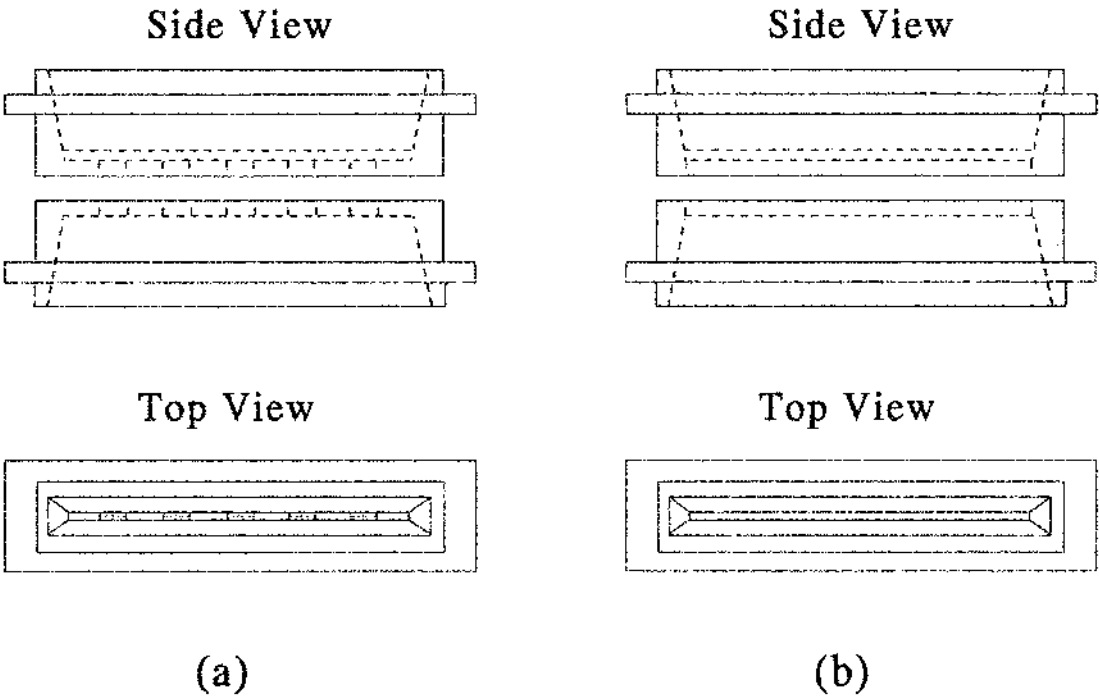
| Virtual impactor | $W_1$<br>(cm) | $W_2$<br>(cm) | $L$<br>(cm)      | $S$<br>(cm) | $Q_0$<br>(L/min) | $Q_m$<br>(L/min) | Re    | $P_{Major}$<br>(KPa) |
|------------------|---------------|---------------|------------------|-------------|------------------|------------------|-------|----------------------|
| Prototype I      | 0.305         | 0.427         | $0.762 \times 1$ | 0.400       | 30               | 2.25             | 4377  | 0.37                 |
|                  | 0.305         | 0.427         | $0.762 \times 1$ | 0.400       | 50               | 1.65–10*         | 7294  | 1.02                 |
|                  | 0.305         | 0.427         | $0.762 \times 1$ | 0.400       | 100              | 5–7.5            | 14589 | 4.23                 |
|                  | 0.305         | 0.427         | $0.762 \times 1$ | 0.760       | 50               | 5                | 7294  | 0.87                 |
|                  | 0.305         | 0.427         | $0.762 \times 3$ | 0.400       | 150              | 15               | 7294  | 1.02                 |
|                  | 0.305         | 0.427         | $0.762 \times 5$ | 0.400       | 250              | 25               | 7294  | 1.02                 |
| Prototype II     | 0.363         | 0.508         | 0.762            | 0.475       | 70               | 3.5–7            | 10212 | 1.37                 |
|                  | 0.363         | 0.508         | 0.762            | 0.475       | 100              | 10               | 14589 | 2.81                 |
|                  | 0.363         | 0.508         | 0.762            | 0.475       | 200              | 2.5–5            | 29177 | 10.8                 |
|                  | 0.363         | 0.508         | 3.05             | 0.475       | 420              | 42               | 15308 | 3.01                 |
|                  | 0.363         | 0.508         | 6.35             | 0.475       | 870              | 43.5–87          | 15231 | 2.92                 |

\*Collector  $C_2$  was used only in the test for Prototype I at  $Q_0 = 50$  L/min and  $Q_m = 5$  L/min; all other tests listed in this table were conducted using collector  $C_1$ .

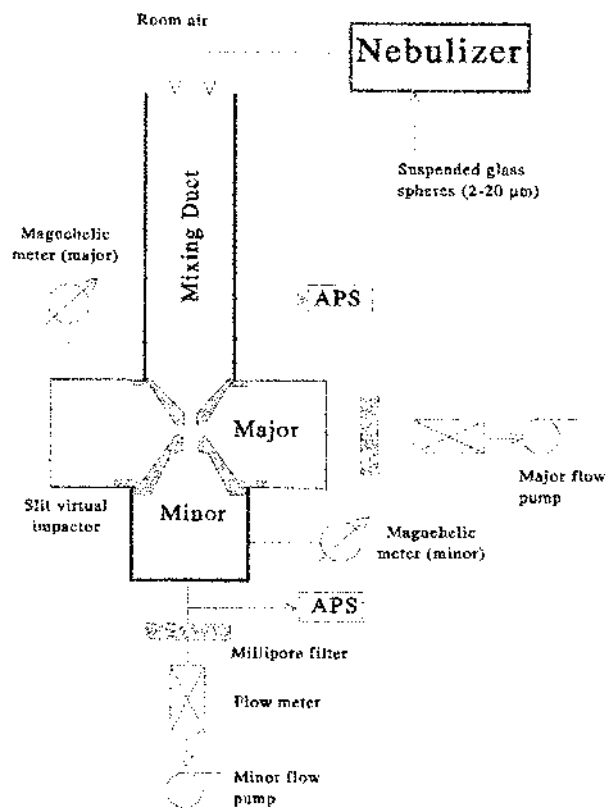
ratio of  $W_2/W_1 = 1.4$ , the same as that in Prototype I. Both the acceleration and collection slit lengths were adjustable, as shown in Figure 2b.

The concentrator system was first tested using laboratory room air. However, the concentration of coarse particles in room air was quite low, so subsequent evaluations were performed using a pocket nebulizer (Retec Model X-70/N), as shown in Figure 3. A flow of a nebulized aqueous suspension of hollow glass spheres (density of 1.1 g/mL and nominal size distribution

of 2–20  $\mu\text{m}$ , Polysciences, Washington, PA) was introduced at the top of the duct, which has internal dimensions of  $W = 6$  cm,  $L = 20$  cm, and  $H = 120$  cm. The duct was used to mix the nebulized glass spheres with room air and to evaporate the liquid water. Also, the use of the duct made it possible to achieve laminar flow before the aerosol entered the prototype impactors. The particle number concentration and size distribution in the duct, major and minor flows were measured using an Aerodynamic Particle Sizer (APS, TSI model 3310). The APS sampling flow



**Figure 2.** Schematic of the multinozzle (a) and long slit (b) configurations.



**Figure 3.** Schematic of the experimental setup for evaluating the high volume slit virtual impactor as used to concentrate coarse particles.

rate was 5.0 L/min. The sampling probes were isokinetically connected to the major, minor, and duct flow channels. When the minor flow was <5.0 L/min, particle free air was added to the minor flow using a millipore filter (Millipore Corp., Medford, MA).

Each APS measurement lasted for 2 min, and the final concentration results presented in this paper were the average of at least five consecutive tests. The relative standard deviation of the average for each particle size was <5%. Note that the nominal size distribution of the hollow glass spheres is based on mass per particle size. Consequently, even though there is a sharp decrease in the mass concentration for particles below 2  $\mu\text{m}$  in diameter, the particle number concentration for sizes below 2  $\mu\text{m}$  is measurable all the way down to the minimum size detectable by the APS (0.7  $\mu\text{m}$ ). The total flow through the duct was measured using a hot wire anemometer (Kurz model 1440). Both the minor and major flows were connected to a 3/4 hp vacuum pump (MFG Corp., Michigan), with flow monitored using mass flowmeters. The pressure drops in both the minor and major channels were monitored with Magnehelic vacuum gages.

The concentration factor of particles for each size range was calculated as the ratio of the particle number concentration measured in the minor flow to that in the duct flow:

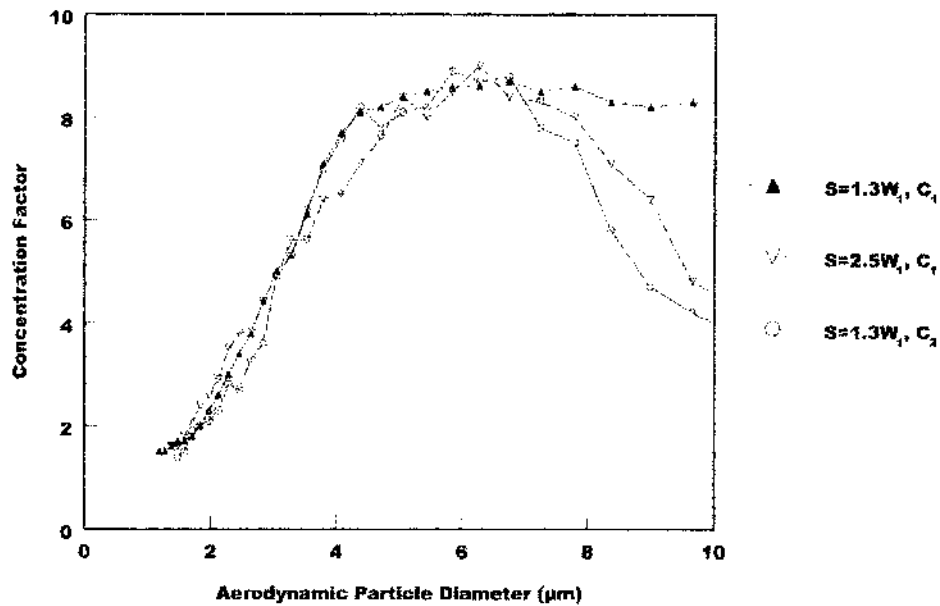
$$\text{Conc. Factor} = \frac{\text{Minor Flow Particle Conc.}}{\text{Duct Flow Particle Conc.}} \quad [1]$$

In order to test for possible distortion of the particle size distribution during the concentration process, the concentration factors were measured for all particles in the size range of 1–10  $\mu\text{m}$ . The particle classification performance of a slit nozzle virtual impactor was evaluated using the conventional collection efficiency curve and internal particle losses as described before (Ding and Koutrakis 1999). The collection efficiency for each particle size was equal to the ratio of the particle number concentration in the minor flow to the sum of the number concentrations in major and minor flows. The internal particle losses were determined for each particle size by comparing the sum of the number concentrations measured in the major and minor flows with those measured in the duct.

## RESULTS AND DISCUSSION

A total flow of 50 L/min and a minor-to-total flow ratio of 10% were chosen so that the Prototype I slit nozzle virtual impactor would have a cutpoint (2.5  $\mu\text{m}$ ) similar to that of the dichotomous sampler. Figure 4 depicts the concentration factor results tested with different  $S$  values and the collection probes  $C_1$  and  $C_2$ . Only the curve with  $S = 1.3 W_1$  and  $C_1$  has a uniform concentration factor (about 8.3) for particles above 4.0  $\mu\text{m}$ . Use of either a larger value of  $S$  or the  $C_2$  collection probe resulted in a reduced concentration factor for particles above 6.0  $\mu\text{m}$ . This may be due to the inertial deposition of large particles on the top of the collection slit as  $S$  increases because the accelerated air sample has more space to expand away from the center of the collection probe. Note that as  $S$  increases, the major flow pressure drop decreases slightly (see Table 1). Deposition losses of large particles on the top and outside wall of the collection probe have also been observed previously in small cutpoint slit nozzle virtual impactors (Sioutas et al. 1994). In the case of the narrower transition cavity ( $C_2$ ), deposition occurs on the inside wall of the collection probe. As shown in Figure 4, however, all three concentration factor curves were very similar near the cutpoint. This is because the classification performance of a virtual impactor is not very sensitive to the gap between acceleration and collection slits (Loo and Cork 1988) and because, once they enter the collection probe, small particles are not lost so easily as large particles.

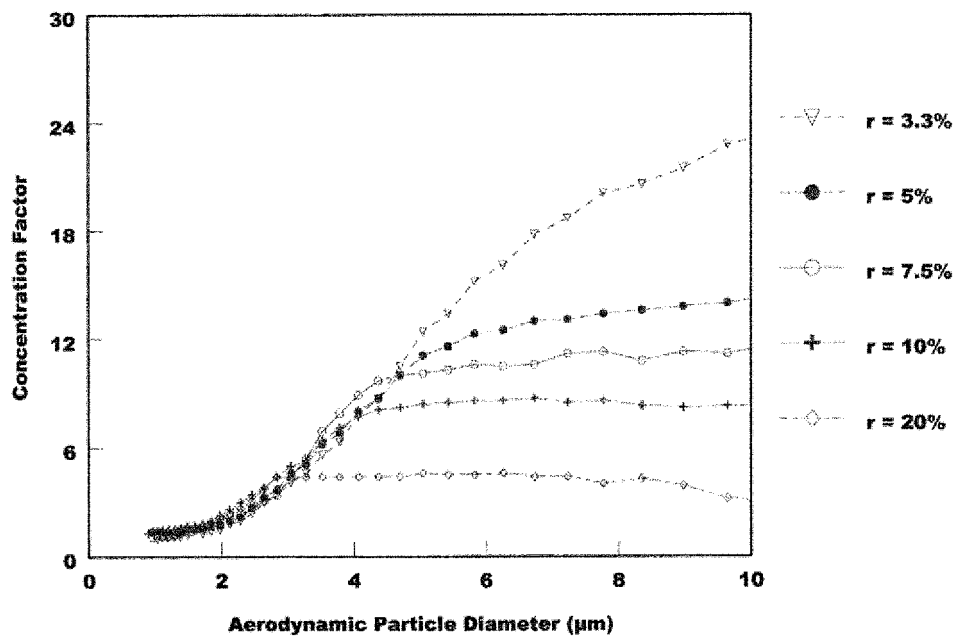
To investigate the effect of the minor-to-total flow ratio ( $r$ ) on the concentration factor, the minor flow varied between 1.65 and 10 L/min, while the total inlet flow was kept at 50 L/min, using  $C_1$  and  $S = 1.3 W_1$ . The results of these tests are shown in Figure 5. As expected, the concentration factor decreased as  $r$  increased. For  $r$  values >5%, the concentration factor eventually became constant for particle sizes above a certain value. As  $r$  values increased above 5%, the plateau started at increasingly smaller particle sizes. This reflects both the decrease of impactor cutpoint with increasing  $r$  and the lower particle losses at higher  $r$  values. However, when the minor-to-total flow ratio reached 20%, the concentration factor decreased slightly for particles above 8.0  $\mu\text{m}$ , probably due to increased turbulence in the collection probe at this high value of the minor flow. For minor-to-total flow ratios of 3.3 and 5%, especially the former,



**Figure 4.** Effect of gap ( $S$ ) and collection probe on the concentration performance of a slit virtual impactor (Prototype I),  $Q_0 = 50$  L/min.

particle losses near the cutpoint were so high that the concentration factor continued to increase with increasing the particle size and never reached a plateau (see Figure 5). In addition, because of particle losses, all of the concentration factors for the plateaus were lower than their corresponding nominal values, which are equal to the total-to-minor flow ratio.

Using the collection probe  $C_1$  and a gap of  $S = 1.3 W_1$ , three and five identical rectangular nozzles were also tested at an  $r$  of 10%, with a flow of 50 L/min per nozzle (Prototype I,  $L(\text{cm}) = 0.762 \times 3$  and  $0.762 \times 5$ , see Table 1). The concentration factors as a function of particle size for the rectangular nozzle numbers  $n = 1, 3$ , and 5 are shown in Figure 6. The nozzle number



**Figure 5.** Effect of minor-to-total flow ratio ( $r$ ) on the concentration performance of a slit virtual impactor (Prototype I),  $Q_0 = 50$  L/min.

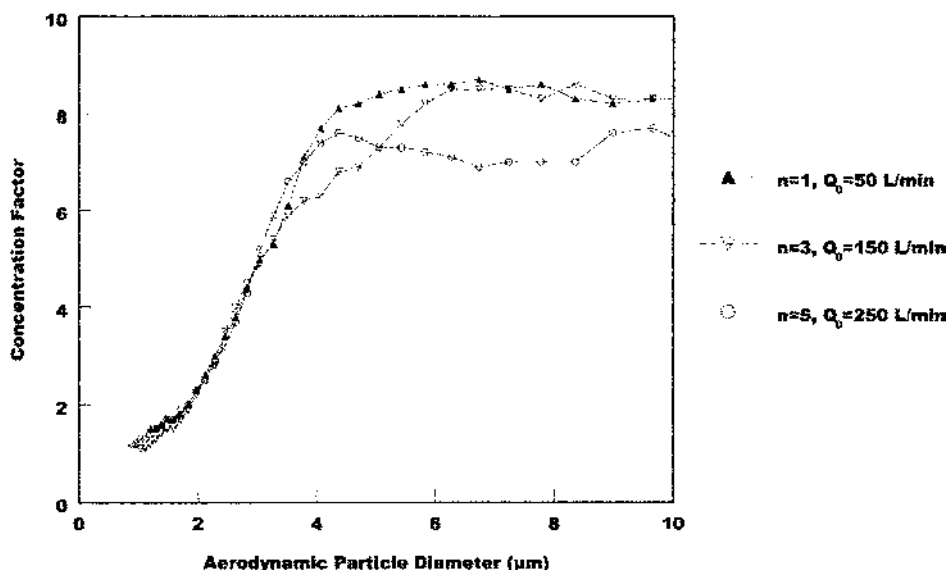


Figure 6. Effect of multinozzle number ( $n$ ) on the concentration performance of a slit virtual impactor (Prototype I).

affected both the particle cut-off and concentration performance. As  $n$  increased from 1 to 5, the concentration factor for particles  $>4.0 \mu\text{m}$  decreased from 8.3 to 7.4.

The results shown in Figures 4 and 6 suggest that if an inlet flow of 50 L/min is used with Prototype I, a minor-to-total flow ratio of 10% or higher is required to concentrate coarse particles without significant distortion of their size distribution. If only a single-stage virtual impactor is used, the maximum concentration factor is only about 8. Therefore, to achieve a sampling flow of 2000 L/min would require 40 rectangular nozzles with  $L = 0.762 \text{ cm}$  or an equivalent single slit with a length of approximately 30 cm. Because it would be costly and impractical to construct such a particle concentrator, and because a concentration factor of 8 is not high enough for inhalation studies, further design development was pursued.

According to our previous study, an increase in particle velocity through the acceleration probe can enable coarse particles to penetrate deeper into the collection probe, thus improving their collection. However, a higher inlet flow rate results in the increase of the major flow pressure drop and the fine particle losses due to a higher Reynolds number (Ding and Koutrakis 1999). The Reynolds number in a slit virtual impactor can be defined as follows:

$$\text{Re} = \frac{\rho W_1 V_0}{\mu} = \frac{\rho Q_0}{\mu L}, \quad [2]$$

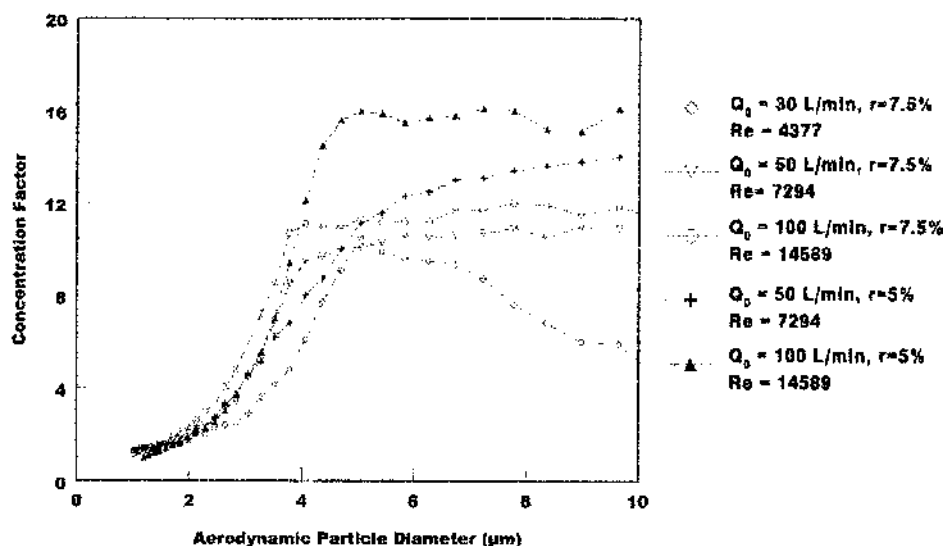
where  $\rho$  and  $\mu$  are the air density and dynamic viscosity, respectively;  $W_1$  is the acceleration slit width;  $V_0$  is the jet velocity;  $Q_0$  is the total inlet flow rate; and  $L$  is the slit length. In order to investigate the effects of inlet flow rate and Reynolds number on the concentration factor, three different total flows ( $Q_0 = 30, 50, \text{ and } 100 \text{ L/min}$ ) were tested on a rectangular nozzle

(Prototype I) at a minor-to-total flow ratio of 7.5%. The two highest flows, 50 and 100 L/min, were also tested at  $r = 5\%$ . The Re values corresponding to  $Q_0 = 30, 50, \text{ and } 100 \text{ L/min}$  were 4377, 7294, and 14589, respectively. Results of these experiments are shown in Figure 7. As is expected, the size cut-off characteristics of the different impactor configurations were different.

For the lowest Re (4377), the concentration factor decreased with an increase in the particle size (with no plateau). The losses of small particles are expected to be minimal for this low Reynolds number. However, the concentration factor of small particles, except for those near  $5.0 \mu\text{m}$ , was still lower than that observed for higher Re values (see Figure 7) because the low inlet flow ( $Q_0 = 30 \text{ L/min}$ ) has shifted the cutpoint size to near  $4.0 \mu\text{m}$  (Ding and Koutrakis 1999).

At higher inlet flows, the concentration factors of coarse particles were significantly enhanced, as shown in Figure 7. The curves corresponding to high Re values ( $\text{Re} = 14589, r = 5\% \text{ and } 7.5\%$ ) exhibited a broader plateau range with higher concentration factor values as compared to the lower Re value curves ( $\text{Re} = 7294, r = 5\% \text{ and } 7.5\%$ ), see Figure 7. In particular, the  $r = 5\%$  curve ( $Q_0 = 100 \text{ L/min}, \text{Re} = 14589$ ) reaches a plateau with a concentration factor near 16. The improved concentration factor at the higher inlet flow is due to the combined effect of the smaller cutpoint size and lower coarse particles losses. At a higher inlet flow, coarse particles gain greater momentum and penetrate deeper into the collector rather than ending up deposited and lost on the collection probe walls during relaxation (Ding and Koutrakis 1999).

The value of  $\text{Re} = 14589$  is considerably higher than that of the dichotomous sampler ( $\text{Re} = 7000$ ) (Loo and Cork 1988). This resulted in higher fine particle losses. To some extent, however, this is desirable for a coarse particle concentrator because it reduces the concentration of fine particles in the coarse-particle



**Figure 7.** Effect of Reynolds number on the concentration performance of a slit virtual impactor (Prototype I).

flow. As shown in Figure 7, the slope of the concentration factor curve at  $Re = 14589$  and  $r = 5\%$  was very steep between 2 and 4  $\mu\text{m}$ . For this curve, while the impactor cutpoint decreased as a result of the increased inlet flow, the concentration factor for 2.5  $\mu\text{m}$  particles was approximately 2, comparable to that for the lower Reynolds number ( $Re = 7294$ ). Finally, it is worth mentioning that by doubling the flow rate and reducing the minor-to-total flow ratio ( $Re = 14,589$  and  $r = 5\%$  versus  $Re = 7294$  and  $r = 10\%$ ), the concentration factor increased by a factor of 2 (approximately from 8 to 16).

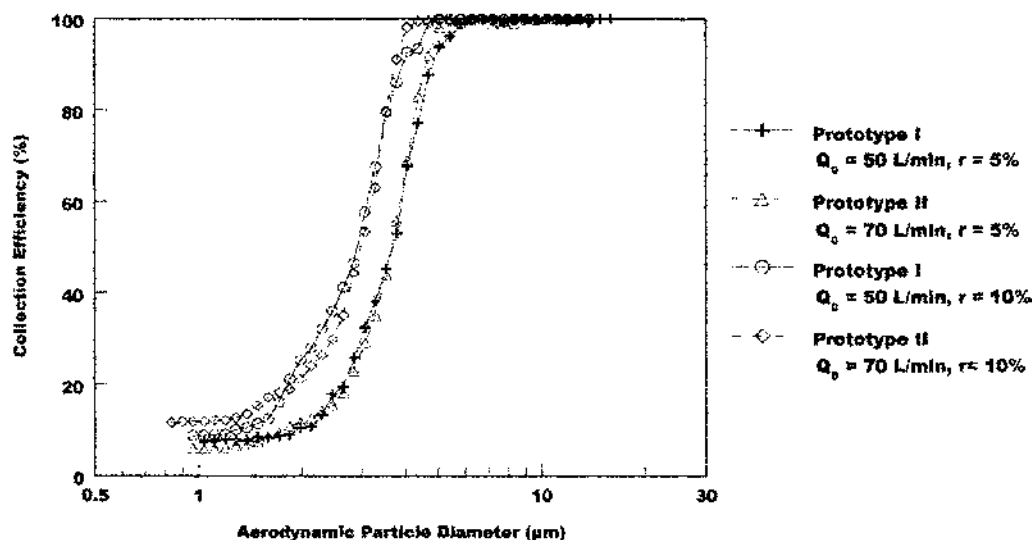
In order to increase the inlet flow per unit slit length, tests were also performed using a wider slit (Prototype II:  $W_1 = 0.363$  cm and  $W_2 = 0.508$  cm). At first, the cut-off characteristics of the Prototype II slit nozzle virtual impactor were investigated using the same slit length as that of Prototype I ( $L = 0.762$  cm, see Table 1). To achieve the same theoretical Stokes number as Prototype I at 50 L/min, the total flow for Prototype II was set at 70 L/min. This corresponds to a Reynolds number of 10212 and a major flow pressure drop of 1.37 KPa. For these conditions, minor-to-total flow ratios of 5% and 10% were tested. Figures 8a and 8b illustrate the collection efficiency results and internal particle losses for both prototypes, respectively. The particle collection efficiency and internal particle losses were determined in the same way as previously described (Ding and Koutrakis 1999). While the Reynolds number of Prototype II was slightly higher than that of Prototype I ( $Re = 7294$ ), the performance of these two virtual impactors appeared to be nearly identical. As expected, the two impactor cutpoints for  $r = 10\%$  were lower than the corresponding ones for  $r = 5\%$ . The particle losses for both prototypes were smaller for the higher  $r$  value, and both configurations presented maximum particle losses near the cutpoint. However, Prototype II presented higher losses for small particles, especially for  $r = 5\%$ . As mentioned above, losses of fine particles do not affect the performance of a coarse particle

concentrator. In addition, both prototypes demonstrated a sharp increase of losses for particles near 10  $\mu\text{m}$  and beyond.

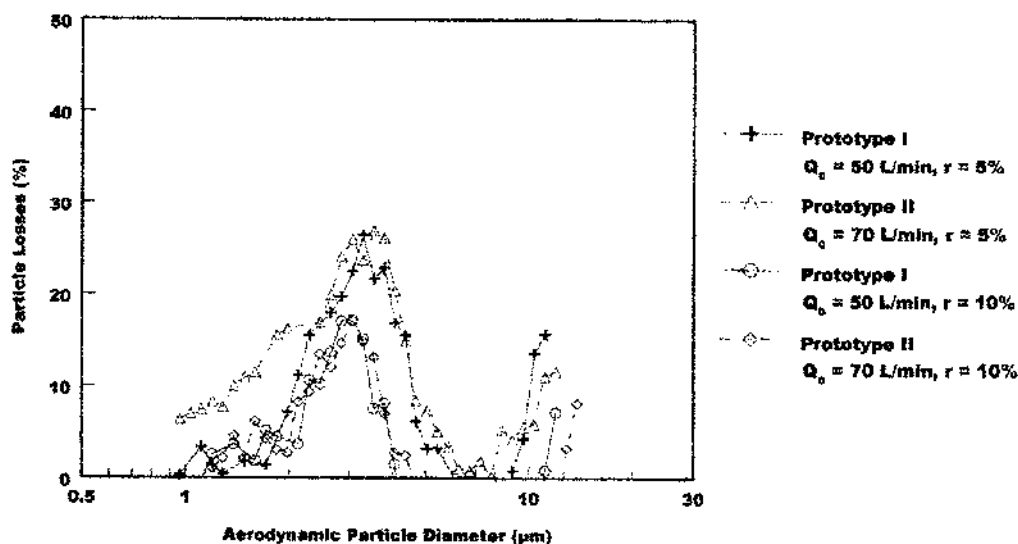
Furthermore, tests were conducted to determine the effect of increasing the slit length on the coarse particle concentration factor using Prototype II. In addition to the rectangular nozzle with  $L = 0.762$  cm, two other longer slits ( $L = 3.05$  and 6.25 cm) of Prototype II were tested (see Figure 2b). The total inlet flow was set at 100, 420, and 870 L/min for  $L = 0.762$ , 3.05, and 6.25 cm, respectively. The minor-to-total flow ratio was maintained at  $r = 10\%$  for all three slits. The Reynolds number and the major flow pressure drop were approximately 15000 and 3.0 KPa, respectively, for all the tests, see Table 1. As shown by the three lowest curves ( $r = 10\%$ ) in Figure 9, all three slits demonstrated a similar concentration performance. Concentrations of coarse particles above 3.5  $\mu\text{m}$  were increased by a factor of about 8.5, while the concentrations of fine particles below about 1  $\mu\text{m}$  were essentially unchanged. The agreement among the three slits implies that the performance of the slit virtual impactor was relatively unaffected by the slit length increase.

In an effort to further increase the concentration factor, lower minor-to-total flow ratios were tested using the Prototype II. First, a test was conducted using the longest slit ( $L = 6.35$  cm) for  $r = 5\%$ . The test results are presented by the curve marked by solid plus in Figure 9. For particles  $d_p > 4$   $\mu\text{m}$ , the concentration factor was approximately 15. However, changes in  $r$  affect an impactor's cutpoint. For example, as  $r$  decreased from 10 to 5% in Figure 8a, the 50% cutpoint increased from 2.5 to 3.5  $\mu\text{m}$ . Similarly, the long slit ( $L = 6.35$  cm) virtual impactor's cutpoint was about 3.5  $\mu\text{m}$  (see Figure 9) for the curve  $Q_0 = 870$  L/min and  $r = 5\%$ . It is necessary to increase the inlet flow to bring the cutpoint back down to 2.5  $\mu\text{m}$ .

Two more tests were conducted using the Prototype II impactor to explore the possibility of increasing the concentration factor while maintaining the impactor's cutpoint at 2.5  $\mu\text{m}$ . The



(a)



(b)

Figure 8. Comparison of the two prototype slit virtual impactors: (a) collection efficiency; (b) particle losses.

slit length ( $L$ ) was 0.762 cm. The inlet flow was 200 L/min. Two minor-to-total flow ratios were tested:  $r = 2.5\%$  and  $1.3\%$ . The results are shown by the two highest curves in Figure 9. These results are very encouraging and suggest that a very high concentration factor with a broad plateau range can be achieved at a low  $r$  value. The concentration factors were approximately 30 and 50 for  $r = 2.5\%$  and  $1.3\%$ , respectively. In particular, the curve for  $r = 2.5\%$  did bring the cutpoint back down to near  $2.5 \mu\text{m}$ . The cutpoint for  $r = 1.3\%$  was a little larger, near  $3.0 \mu\text{m}$ , as expected for a smaller  $r$  value. Similarly, this cutpoint can be decreased by further increasing the inlet flow rate. Although the major flow pressure drop increased to 10.8 KPa

for these two tests with an increased inlet flow rate (see Table 1) the minor flow pressure drop was undetectable.

## CONCLUSIONS

A high volume slit nozzle virtual impactor which can be used to concentrate coarse particles was designed and evaluated. The initial rectangular nozzle virtual impactor design (Prototype I) used a slit width equivalent to the diameter of the round nozzle dichotomous sampler. Under the typical dichotomous sampling conditions ( $Re = 7294$ ,  $r = 10\%$ ), this prototype performed well and provided 5 L/min of coarse particles concentrated by a factor

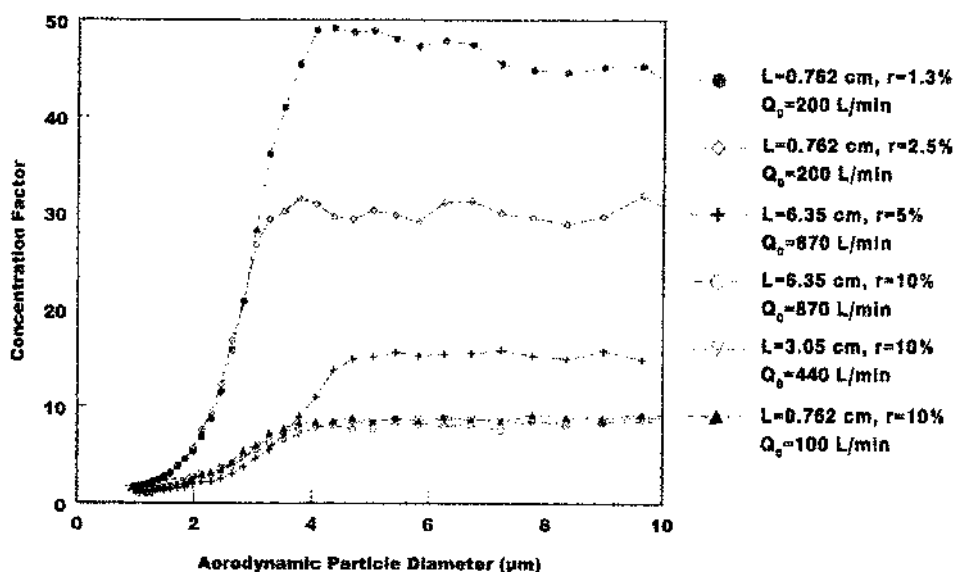


Figure 9. Effect of slit length ( $L$ ) on the concentration performance of a slit virtual impactor (Prototype II).

of about 8. The use of a multiple nozzle slit virtual impactor can make it possible to increase the total inlet flow. However, the cut-off performance and particle concentration factor were both affected due to jet interaction. Even if the performance of a multiple nozzle virtual impactor were improved by using better alignment, such a system may still be unsuitable because of its size and cost.

A second slit nozzle impactor (Prototype II) that used a wider slit was constructed. Although this impactor operated at a slightly higher major flow pressure drop to achieve the desired size cut-off, its performance was similar to that of the first prototype. Increasing the slit length had no significant effect on the coarse particle concentration performance. A slit nozzle with a length of 6.35 cm operating at a total flow of 870 L/min exhibited the same concentration performance as that of the short slit,  $L = 0.762$  cm and  $Q_0 = 100$  L/min. Decreasing the minor-to-total flow ratio increased the concentration factor. For a minor-to-total flow ratio of 5%, the long slit virtual impactor ( $L = 6.35$  cm) provided 43.5 L/min flow of coarse particles concentrated by a factor of 15. An even higher concentration factor was achieved by further reducing  $r$ . A single-stage virtual impactor (Prototype II) increased the coarse particle concentrations by a factor of 30 or even up to 50 as  $r$  decreased to 2.5% or 1.3%, respectively. The impactor's cutpoint was maintained at  $2.5 \mu\text{m}$  by increasing the total inlet flow.

The results of our study suggest that the optimum design of a slit nozzle virtual impactor for a coarse particle concentrator is not necessarily the most appropriate design for a sample collector used to classify coarse and fine particles, such as the dichotomous sampler. The coarse particle concentrator was concerned with only the collection of coarse particles and did not consider fine particle losses. As a result, the virtual impactor in a concentrator operated at a higher Reynolds number than that of the dichotomous sampler. Under these conditions, coarse

particle losses were reduced because the coarse particles could penetrate more effectively into the collection probe. This resulted in a uniform concentration factor over a wide range of particle sizes.

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